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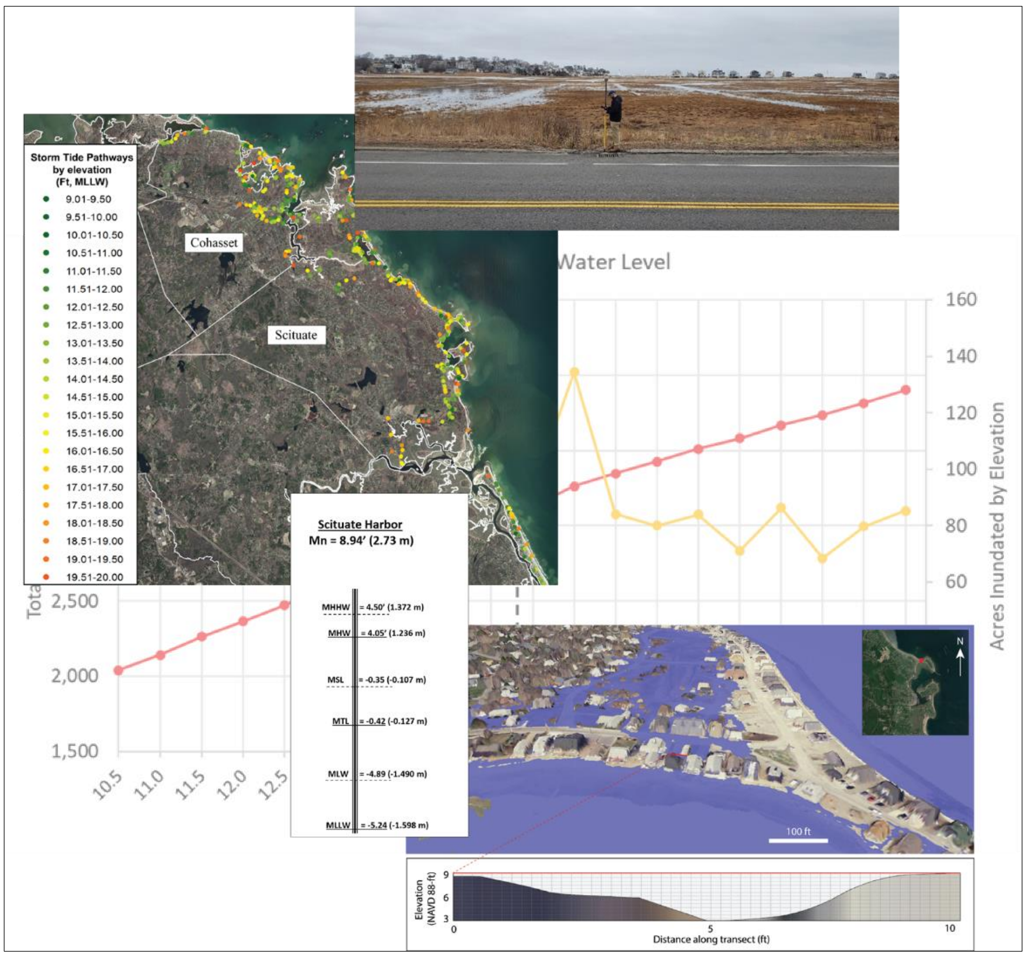
Mapping Storm Tide Pathways in Scituate and Cohasset: Assessing Coastal Vulnerability to Storms and Sea Level Rise



A report prepared for the Towns of Scituate and Cohasset, Massachusetts

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by the Coastal Processes and Ecosystems Lab at the Center for Coastal Studies
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EXECUTIVE SUMMARY

Managers, first-responders, and public works professionals in low-lying coastal communities need information in real-time, and for future planning purposes, on a scale commensurate with the duties they are charged with completing. The mapping of storm tide pathways provides town staff and the public with critical information on the precise location of potential flooding that enables communities to address each individual pathway and prevent future inundation. Further, in collaboration with the Southern New England Weather Forecast Office of the National Weather Service (SNEWFO-NWS), the incorporation of these data into the NWS Coastal Flood Threat and Inundation Mapping webpage (http://www.weather.gov/box/coastal) will provide real-time total water level predictions for coming storm events to town staff and the public.

Field work necessary to verify and locate pathways accurately was conducted from November 2019 through March 2020 throughout the two towns. A total of 443 pathways were identified in the initial desktop analysis. After field surveys, 28 pathways were added and 6 were removed for a total of 465 storm tide pathways in the study area. The Town of Cohasset has 166 pathways, the Town of Scituate has 299. In addition to the 28 pathways added in the field, the location of 202 pathways (43.4%) were moved more than 1 m horizontally during field surveys. Presently, the towns of Scituate and Cohasset flood regularly during high water storm events, but to illustrate the nature of the future threat faced by low-lying communities this study has identified 54 pathways between 14.8 ft - 15.8 ft (MLLW) that have not flooded in recorded history, yet lay less than 12 inches above the storm of record for the area.

The storm tide pathways data and maps are digital but can be used in a number of ways. Hardcopy maps can be generated for training purposes, field use or in the event of a power loss, online apps can be produced for use by town staff and the public and offline apps can be created for use by first responders and other staff to use during internet loss, to train, or plan future mitigation efforts and/or assess vulnerabilities. Working with the SNEWFO-NWS, Center for Coastal Studies (CCS) staff reformatted data generated from this project within Cohasset and Scituate to conform to standards needed to be hosted on the NWS Coastal Flood Threat and Inundation Mapping website. This website now combines NWS storm surge forecasts with accurate elevation data and storm tide pathway locations to provide municipalities with reliable information of the severity of coastal inundation events. These improved and easily accessible data will help communities to avoid, mitigate and prepare for these increasingly severe flooding events.

PROJECT BACKGROUND AND OVERVIEW

Massachusetts has many low-lying coastal communities that have historically been vulnerable to inundation associated with coastal storms and flooding. These threats are further exacerbated by rising sea levels as flooding events, superimposed onto that sea level rise, increase in frequency and magnitude, including nuisance flooding as well as during coastal storms (storm surge and wave setup). Recent local storms such as the Blizzards of 2015 and 2018, as well as Katrina, and Sandy, highlight management challenges that are becoming more acute as current climate conditions appear to be producing higher intensity or longer duration storms accompanied by large storm surges that result in significant coastal flooding events.

Consensus among scientists indicates that sea levels are rising at an increasing rate. Therefore, much attention has been focused on efforts that enhance adaptation and increase resiliency related to climate change in coastal settings. As shown in Figure 1, projections vary from a low of 0.15 meters (0.5 feet) to a high of 2 meters (>6 feet) by the end of this century, recently some projections have an even higher rate of increase by 2100. However, such a broad range of projected sea level rise creates significant uncertainty for coastal managers faced with identifying potential hazards

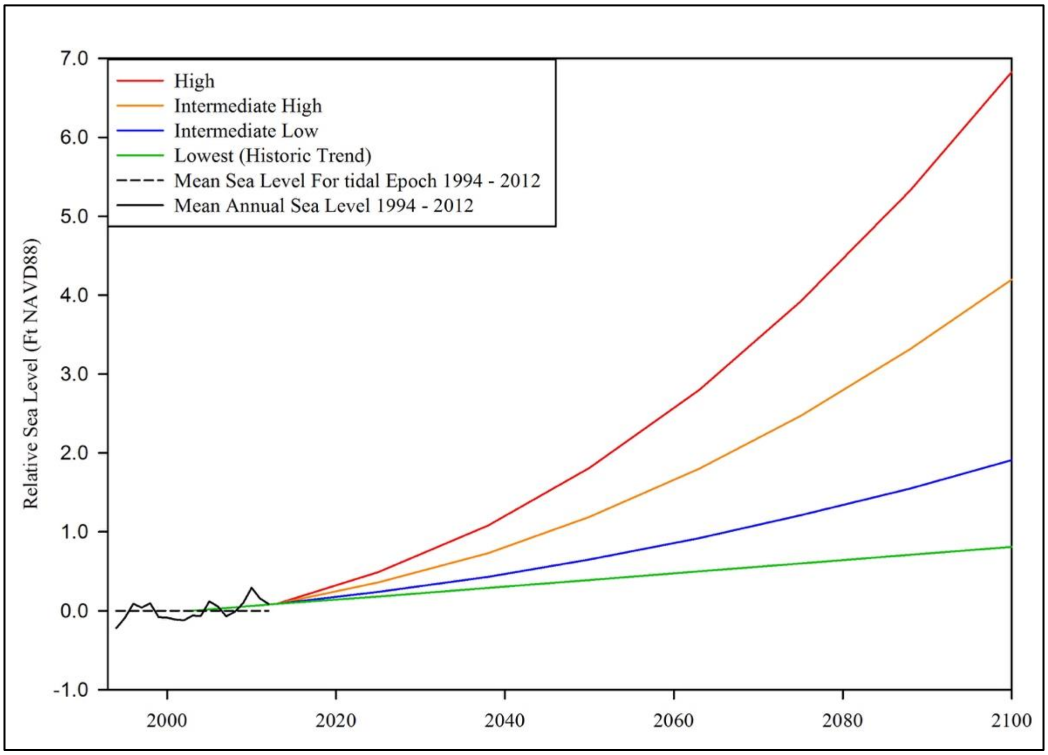

Figure 1. Relative sea level rise scenario estimates (in feet NAVD88) for Boston, MA. Modifed after Figure 5 in, Sea Level Rise: Understanding and Applying Trends and Future Scenarios for Analysis and Planning. Massachusetts Office of Coastal Zone Management, December 2013. Available at: www.mass.gov/eea/docs/czm/stormsmart/slr-guidance-2013.pdf.

to, and vulnerabilities of property and infrastructure, prioritizing response actions, and demonstrating to local governments the need to undertake actions in spite of the unavoidable uncertainties inherent in century-scale sea level rise projection scenarios. Annual or even decadal planning horizons are not easily defined or addressed within the context of sea level rise. Further, discussions and effective response actions, implementable at the local level, are difficult to identify.

In addition to the issue of defining a suitable planning horizon to address sea level rise, the ability of coastal managers to effectively and efficiently identify potential vulnerabilities and to educate residents and community leaders about the threats associated with coastal inundation has been severely limited by the lack of accurate elevation data at a scale that is usable at the community level. For example, Flood Insurance Rate Maps (FIRMS), produced by the Federal Emergency Management Agency (FEMA), have long been standard planning resources for coastal communities, however, these maps were intended to facilitate the determination of flood insurance rates and historically have lacked the topographic detail necessary for focused planning efforts. Until recently the accuracy of relatively low-cost elevation data has been appropriate only for general planning at regional scales and not appropriate for identifying inundation and flooding impacts over timeframes that meet the needs and budgets of most municipalities. Numerical modeling of storm surge, sea level rise, waves, or sediment transport (coastal erosion) can be effective for regional efforts to understand coastal evolution but can also be cost prohibitive. Further, vertical uncertainties associated with some of these models can be too coarsely scaled to inform site-specific decisions expected of local coastal managers.

Based on the long-range projections of sea level rise, and the catastrophic damages associated with large coastal storms, much attention is focused on long term strategies to reverse current climate trends and slow the rate of, or reverse sea level rise. Strategies to reduce Green House Gas emissions, to promote green energy, and to deal with rising temperatures, glacial ice melt, and thermal expansion of sea water over the next hundreds of years are being discussed and debated at the international, national, and state levels. Clearly the planning and costs to confront these issues are long term and capital intensive. Lost in these discussions are viable hazard planning strategies that can be adopted and implemented at the local level within the shorter planning horizons and financial means of local municipalities.

Recognizing the limited financial and technical resources of coastal communities and their unique geography, local responses and strategies to sea level rise and climate change need to operate effectively in the context of short-term planning horizons and frequently changing leadership. Specifically, short term planning efforts should identify actions or responses that are:

1) Achievable within an appropriate time frame (e.g., 30 years)
2) Implementable with current technology
3) Financially feasible

4) Politically viable (i.e., not extreme – e.g., wholesale retreat)
5) Adaptable to changing future scenarios
6) Focused on both infrastructure and natural resources

While sea level rise projections are clearly critical for longer term planning considerations, particularly for large scale efforts, actual past, present, and future storm tide elevations may provide a more effective means of characterizing local coastal hazard vulnerabilities for community level planning actions. Figure 2 depicts estimates of historical storm tide elevations for the Boston area (an easterly facing shore) for various storms for the 17th - 21st centuries. The current projections for the highest sea level rise scenario and the NOAA regression rate scenario based on current tide gauge data obtained from the Boston tide gauge are shown through the year 2100.

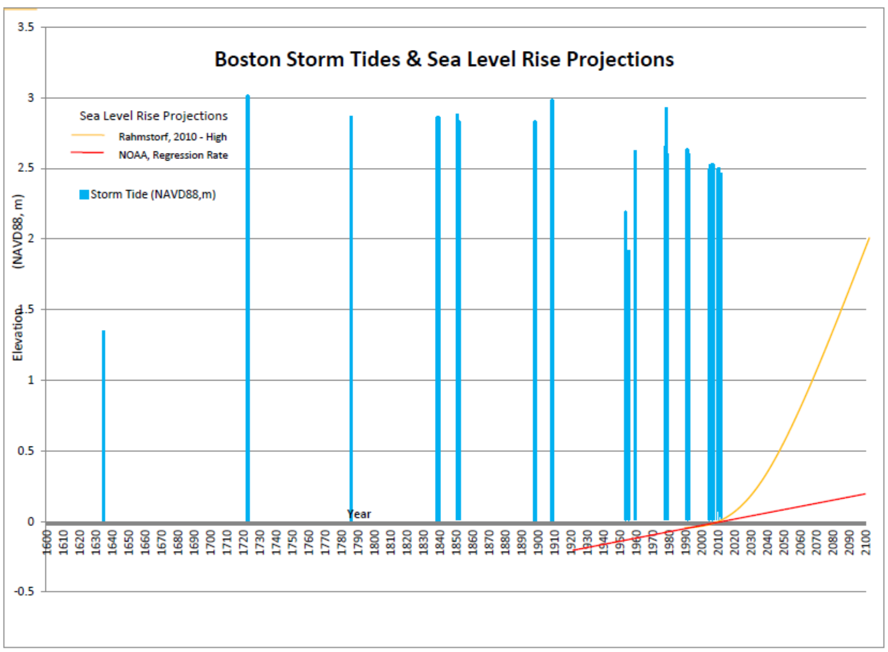

Figure 2. Historical Storm tides and sea level rise.

In recent history the "Blizzard of '78" had been the storm of record for Boston and areas to the north of Cape Cod. However, the January 4th, 2018 storm surpassed the total water level for the 1978 storm for much of the same area and is now the new storm of record. Interestingly, the plot indicates that the storm tides and associated flooding for Boston reached an elevation of approximately 1 meter (~3 feet) above that of the highest sea level rise projection for the year 2100. Illustrating the point that municipalities are more susceptible to storm-related flooding now, and that preparing for these storm events can help communities prepare for future sea level rise. The plot further reveals that earlier estimates of storm tide heights have probably equaled or exceeded the 2018 maximum numerous times since the 17th century.

Identifying potential future storm tide heights, coastal flooding extents, and areas of potential vulnerability using historical data provides several benefits to coastal communities. First, using actual historical storm tides data to identify coastal hazard vulnerabilities increases the certainty of planning efforts by removing sea level rise and the disparity of projections (Figure 1) from the discussion of the most appropriate sea level rise elevation upon which to base short term planning responses. Sea level rise notwithstanding, storm tides of significant magnitude have been experienced in the past and will continue to be experienced again in the future. Second, storms of record provide an accurate, actual (i.e., indisputable) reference elevation that towns can plan for when history repeats or surpasses itself. Finally, as discussed below, using emerging data gathering technologies to identify inundation impacts, will yield valuable information that can be used by coastal communities to plan and implement ground level strategy in response to sea level rise.

METHODS

Accurate Elevation Data, Record Inundations and Potential Pathways

Over the past ten years, light detection and ranging (lidar) surveys have emerged as a cost-effective and constantly improving source of coastal elevation data. Covering broad geographic areas with horizontal accuracies typically on the order of 1 meter (~3 ft) and vertical accuracies on the order of 0.15 – 0.30 m (~0.5 - 1.0 ft), this relatively high resolution topographic information is a valuable initial resource for coastal managers developing inundation scenarios that can be used to begin to visualize threats associated with coastal storms. Despite improvements in vertical accuracy, the use of lidar alone to map areas of storm vulnerability and to develop community response strategies, however, has been limited. Recognizing data limitations, current guidelines for inundation modeling using lidar elevation data sets with vertical accuracies of 15 cm (0.5 feet) recommend analyses be performed at increments of 58.8 cm (~2.0 feet), a resolution clearly too coarse for the development of short-term, local action items. However, this base level information, when supplemented with area-specific high-resolution elevation data to reduce uncertainties, can be used to identify, and prioritize potential coastal hazards at the local level in a cost-effective manner.

The primary goal of this project was to supplement the lidar base map with more accurate GPS survey data to map the routes through which ‘storm tides’ (discussed in more detail below) will pass, threatening vulnerable areas with inundation of varying depths. For purposes of this project, these locations have been termed ‘storm tide pathways’. For this project, recently available elevation data (lidar from 2 USGS data sets: the 2013-2014 “Sandy Project” and 2011 for some inland areas) and state-of- the-art data visualization software (Fledermaus™) was used as the basis for the initial screening to identify potential pathways for further analysis. These pathways are subsequently investigated in the field using centimeter-scale GPS survey equipment to verify its horizontal and vertical location. Continuing to use the lidar as a base map to be verified in the field, this process is repeated as an iterative sensitivity analysis to identify threshold pathways associated with key historical storms and higher or lower storm- tide elevations to provide a foundation for local planning actions.

Generally, storm tide pathways (STPs), by virtue of their elevation relative to the elevation of the storm tide, provide a direct connection between coastal waters and low-lying inland areas. Examples of pathways that may serve as direct hydraulic connections include: low spots in built environment (e.g., roads, walkways, dikes, seawalls, etc.); and low spots in natural topography (e.g. low lying earthen berms, barrier beaches, and dune systems susceptible to erosion and breaching). Low-lying infrastructure can also serve as unintended conduits (e.g., stormwater systems, sanitary sewers, electrical/utility conduits), however, analysis of potential conduit hydraulics should be evaluated by a qualified engineer to accurately assess potential vulnerabilities.

As discussed above, to minimize the uncertainties associated with sea level rise projections and to provide information that is reliable within a 30-year planning horizon, this study relies on documented elevation records associated with the flood elevations of documented coastal storm tides. Research of available records and studies indicates that, as for Boston, the storm of record for the Scituate Cohasset area would appear to be the January 4th Blizzard of 2018. The associated storm tide was 9.66 feet (2.95 meters) referenced to the North American Vertical Datum of 1988 (NAVD88). This elevation represents an actual storm tide elevation that is approximately 5 feet above contemporary mean higher high water (MHHW) and approximately 11 feet above contemporary mean sea level (MSL) for the study area.

Cohasset/Scituate Tidal Profile

As discussed above the use of the historical record to supplement predicted storm and spring tide elevation data can provide valuable baseline information to Emergency Managers, Public Works Departments, Harbormasters, and Coastal Resource Managers. Independent of long-term sea level rise projections, storm surge projections considered in the context of storms of record and accurate ground elevation data can be used to map storm tide pathways with a high degree of certainty. As demonstrated in previous CZM Resiliency Grant projects with the towns of Provincetown, Nantucket, and Truro, when referenced to a common vertical datum that spans the land-sea interface, these data can be used by towns as the basis for short-term community planning decisions and real-time decisions necessary to confront impacts associated with coastal storms and related storm surge.

Characterizing Coastal Inundation

As relative sea level continues to rise, many coastal communities are beginning to experience occasional minor flooding with the higher tides of the month (e.g., spring tides). Often referred to as *nuisance flooding* since it is rarely associated with dramatic building or property damage, this type of flooding is becoming more frequent resulting in chronic impacts that include overwhelmed drainage systems, frequent road closures, and the general deterioration of infrastructure not designed to withstand saltwater immersion (Sweet, *et. al.*, 2014).

In addition to minor monthly inundation, many coastal communities also experience damaging flooding associated with relatively short duration, high intensity coastal storms. The term *storm tide* refers to the rise in water level experienced during a storm event resulting from the combination of *storm surge* and the astronomical (predicted) tide level. Storm tides are referenced to datums, either to geodetic datums (e.g., NAVD88 or NGVD29) or to local tidal datums (e.g., mean lower low water (MLLW)). *Storm surge* refers to the increase in water level associated with the presence of a coastal storm. As the arithmetic difference between the actual level of the storm tide and the predicted tide height, *storm surges* are not referenced to a datum.

In addition to storm surge magnitude, the time at which the maximum surge occurs relative to the stage of the astronomical tide is a critical component of the maximum storm tide elevation experienced during any particular storm. The significance of this relationship is illustrated by the following example.

Prior to January 4, 2018, the storm of record for the Boston Tide Gauge (#8443970) occurred on February 7, 1978 with a maximum storm tide elevation of 9.59' referenced to the North American Vertical Datum of 1988 (NAVD88). Occurring at approximately the time of the predicted or astronomical high tide, the storm surge was approximately 3.5 feet. By comparison, the maximum storm tide elevation experienced during the blizzard of January 27, 2015 was 8.16' NAVD88. Occurring shortly after the astronomical high tide, this elevation resulted from the combination of an astronomical tide height of 4.79' NAVD88 and a storm surge of 3.37 feet. Significantly the maximum storm surge for this event was observed to be 4.5 feet, however, because it occurred close to the time of low water the corresponding storm tide elevation was only -1.1' NAVD88. Had the maximum storm surge occurred approximately 6 hours earlier at the time of the astronomical high tide, the resulting storm tide elevation would have been 9.2' NAVD88, approximately 5 inches below the elevation of the storm of record.

Recognizing the significance of not only the magnitude of the predicted storm surge but when it will occur relative to the stage of the tide, the National Weather Service (NWS) in Norton, MA maintains an informative website that estimates storm surge and total water level at various Massachusetts locations (http://www.weather.gov/box/coastal) as coastal storms approach New England. This project supplements information developed in previous CZM Resiliency projects for Provincetown and Truro to provide the NWS Norton office with an additional data set of accurately mapped storm tide pathways that can be incorporated into the coastal storm surge website to reduce the uncertainty and improve the utility of storm tide inundation forecasts for the Cohasset/Scituate area.

Creating a Storm Tidal Profile for the Cohasset and Scituate Mapping

The effects of storm tides on coastal communities are dependent on many factors. These include the landscape setting of the community (e.g., east facing v. south facing shores); the elevations of astronomical tides (e.g., the elevation of mean high water (MHW) in Boston Harbor is 4.31 feet NAVD88 v. the elevation of mean high water for Woods Hole is 0.56’ NAVD88); general characteristics of astronomical tides (e.g., the average range (MHW minus MLW) of Boston Harbor tides is 9.49 feet while that of Woods Hole tides is only 1.79 feet); topography (e.g., the elevation of the land relative to the community tidal profile); nearshore bathymetry (e.g., the deeper the water relative to shore, the greater the potential wave energy); topographic relief (i.e., a measure of the flatness or steepness of the land with flatter areas more sensitive to small changes in water levels); the nature of coastal landforms (e.g., the rock shorelines of the North Shore v. the dynamic sandy shorelines of Cape Cod); and the vertical relationship between historical community development and adjacent water levels (e.g., development in Boston began in the early 17th century with the water levels at that time influencing the elevation of not only pile supported structures but large scale landmaking – filling – efforts).

With such variation in physical characteristics, the initial step in the identification of storm tide pathways for a community is the development of a datum-referenced tidal profile that characterizes average tidal heights, nuisance flooding, and storm tides. In addition to the more common tidal datums of mean high water springs (MHWS), mean higher high water (MHHW), mean high water (MHW), and mean sea level (MSL), the tidal profile used for this study includes datum referenced storm tides of the past, including the elevation of the maximum storm tide experienced (i.e., the storm of record) for the area. As sea levels continue to rise, an estimate of potential future storm tides is provided by adding four feet to the storm of record (Zervas, 2009).

The Scituate Harbor tide station (#8445138) was installed by the National Oceanic and Atmospheric Administration (NOAA) on May 23, 1990 and discontinued on September 14, 1990. Based on this tide data, NOAA developed tidal datum values for the 1983-2001 National Tidal Datum Epoch. The current tide station in Scituate Harbor was installed by NOAA and the University of Massachusetts Boston later. This station reports real time tidal observations and is accessible at https://water.weather.gov/ahps2/hydrograph.php?wfo=box&gage=SCTM3.

The primary benchmark for Tide Station #8445138 was established by NOAA in 1990. Designated as Tidal Benchmark #5138 A, it is located in the bend of a concrete seawall in the northeast corner of the Scituate Harbor Marina parking lot. The Center for Coastal Studies (CCS) occupied this point with its RTK-GPS instrument on January 13th, 2020 and obtained an elevation of 3.108 meters (10.28 feet), NAVD88. CCS occupied a second tidal benchmark (Benchmark 844 5138 B 1990) on March 21, 2020 and obtained an elevation of 3.119 meters (10.23 feet), NAVD88. These elevations agree closely with the value reported in the National Geodetic Survey database for the same point (OPUS PID# BBBJ43) observed in 2009 (3.060 meters, NAVD88). Since tidal datums calculated from the CCS occupied benchmarks agreed within 0.03 feet (0.009 meters), Tidal Benchmark #5138 A, the primary station benchmark, was used to develop the tidal profile in Figure 3 and Table 1.

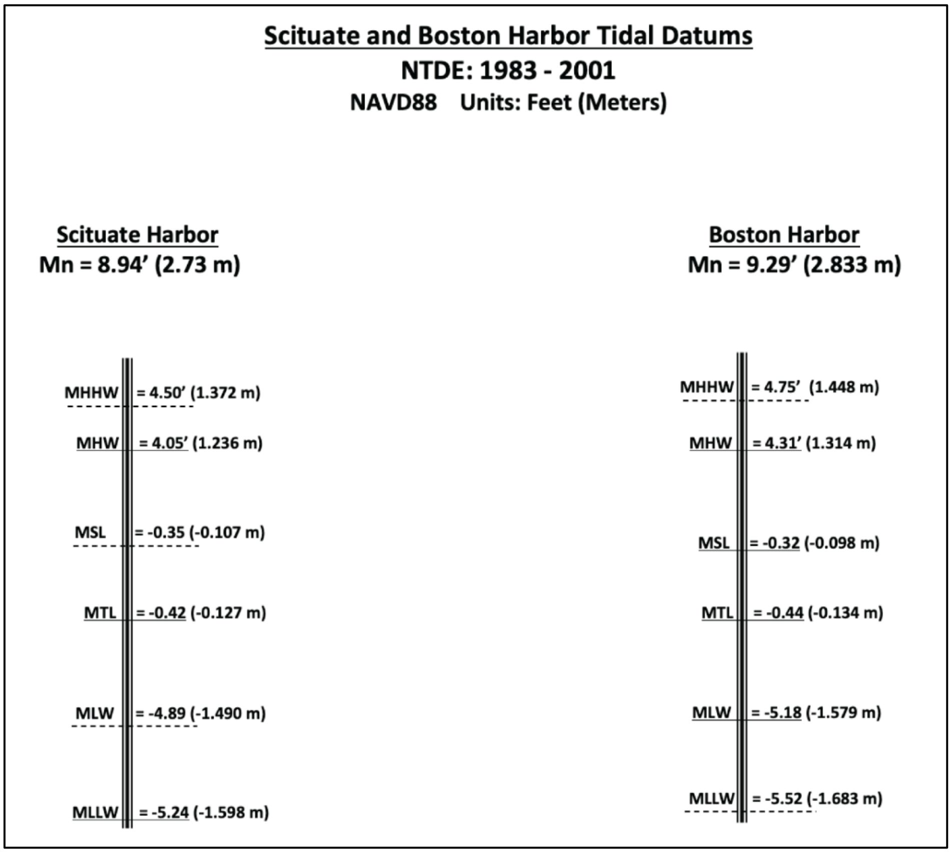

Figure 3. Tidal datum profiles for Boston and Scituate Harbors.

The relationship between MLLW and NAVD88 is shown graphically on Figure 3 along with tidal datums computed for the 1983 to 2001 National Tidal Datum Epoch (NTDE) based on benchmark information provided the NOAA COOPs program (https://tidesandcurrents.noaa.gov/benchmarks.html?id=8445138).

The results of the CCS observations were used to develop the following relationship between local MLLW and NAVD88.

$$\text{Elevation}_{\text{MLLW}} + (-5.24 \text{ feet}) = \text{Elevation}_{\text{NAVD88}}$$

NOAA tide station #8443970 located in Boston Harbor is a primary tide station with continuous tide readings beginning on May 3, 1921. It has been used historically as the control station for published tide information for Scituate Harbor. Figure 3 depicts tidal profiles referenced to NAVD88 for Boston Harbor based on 19 years of tidal readings, and Scituate Harbor, based on 3 months of tide readings in the summer of 1990 adjusted to the 1983-2001 NTDE. Referencing tidal heights to NAVD88 allows for Scituate and Boston Harbors to be compared directly and as shown in this figure the tidal profiles for the two harbors are very close.

Table 1 Scituate Harbor Tidal Profile (Station 8445138).

Events and Datums	NAVD 88 (FT)	MLLW (FT)	Comments
Boston Harbor Storm of Record plus 4 Feet	13.66	18.90	Upper Limit of Storm Tide Pathway Analysis
January 4, 2018 Maximum Storm Tide (Boston Harbor)	9.66	14.90	Storm of Record Based on NOAA Tide Station #8443970
Blizzard of 1978 previous Storm of Record (Boston)	9.57	14.81	NOAA Tide Station #8443970
January 4, 2018 Maximum Storm Tide (Scituate Harbor)	9.54	14.78	NOAA/UMASSBOS Tide Gauge
MHWS	4.69	9.93	NOAA Tide Station #8445138
MHHW	4.50	9.74	NOAA Tide Station #8445138
MHW	4.05	9.30	NOAA Tide Station #8445138
MSL	-0.35	4.89	NOAA Tide Station #8445138
MTL	-0.42	4.82	NOAA Tide Station #8445138
MLW	-4.89	0.35	NOAA Tide Station #8445138
MLLW	-5.24	0.00	NOAA Tide Station #8445138

Developing the Cohasset/Scituate Tidal Profile

As shown by Figure 3, the values of the tidal datums for Boston and Scituate Harbors are extremely close, with the values for Scituate Harbor generally 0.25’ ± lower than those of Boston Harbor**.** Due to these similarities in tidal profile and geographic orientation, the elevation of the Boston Harbor storm of record, previously the Blizzard of ’78 and currently the January 4, 2018 winter storm, was compared with the Scituate tide gauge and found to be within 0.12’ feet on the same date. The maximum 2018 water level for Boston Harbor was observed to be 9.66’ NAVD88 and 9.54’ NAVD88 for the same storm in Scituate Harbor. Table 2 summarizes the highest water levels for Boston Harbor since May 3, 1921 when tidal station #8443970 was installed while Table 3 summarizes the highest water levels recorded for Scituate Harbor since 2010.

Table 2. Maximum Water Levels for Boston Harbor since May 3, 1921 Boston Harbor (Station #8443970) Highest Recorded Water Levels

Rank	Date	NAVD88 (Ft.)	MLLW (Ft.)
1	1/4/2018	9.66	15.18
2	2/7/1978	9.59	15.11
3	1/2/1987	8.69	14.21
4	10/30/1991	8.66	14.18
5	1/25/1979	8.53	14.05
6	12/12/1992	8.52	14.04
7	12/29/1959	8.49	14.01
8	4/18/2007	8.29	13.81
9	5/25/2005	8.27	13.79
10	2/19/1972	8.19	13.71
11	12/27/2010	8.19	13.71
12	5/26/2005	8.16	13.68
13	1/27/2015	8.13	13.65
14	5/26/1967	8.1	13.63
15	6/5/2012	8.07	13.59
16	3/4/1931	7.97	14.49
17	11/30/1944	7.87	19.39
18	1/20/1961	7.85	13.37
19	4/21/1940	7.38	13.35

Table 3 Maximum Water Levels for Scituate Harbor since 2010. Scituate Harbor (Station #8445138) Highest Recorded Water Levels

Rank	Date	NAVD88 (Ft.)	MLLW (Ft.)
1	1/4/2018	9.54	14.78
2	3/3/2018	9.35	14.59
3	3/2/2018	9.12	14.36
4	1/30/2018	8.60	13.84
5	1/12/2012	7.83	13.07
6	1/2/2010	7.78	13.02
7	3/4/2010	7.72	12.96
8	3/1/2010	7.72	12.96
9	1/21/2011	7.57	12.81
10	1/20/2019	7.54	12.78
11	11/25/2018	7.52	12.76
12	3/22/2019	7.39	12.63
13	2/26/2010	7.37	12.61
14	3/31/2010	7.29	12.53
15	11/24/2011	7.27	12.51
16	11/27/2018	7.27	12.51
17	10/30/2011	7.25	12.49
18	7/24/2013	7.25	12.49
19	3/5/2010	7.22	12.46

Since no long-term storm of record has been documented by the Scituate Harbor tide gauges, the elevation of the January 4, 2018 storm of record for Boston Harbor was used to complete the Cohasset/Scituate tidal profile (Table 3) and map potential STPs within the towns of Cohasset and Scituate. As shown in this table, the maximum storm tide elevation considered in this analysis was the storm tide of record plus 4 feet (13.66' NAVD88). To evaluate potential nuisance flooding associated with more frequent non-storm tidal events, the STP analysis of potential storm flooding began at the elevation of mean high water (4.05' NAVD88).

A WORD ABOUT DATUMS

A datum is a reference point, line, or plane from which linear measurements are made. Horizontal datums (*e.g.*, the North American Datum of 1983 (NAD83)) provide a common reference system in the x,y-dimension to which a point's position on the earth's surface can be referenced (*e.g.*, latitude and longitude). Similarly, vertical datums provide a common reference system in the z-direction from which heights (elevation) and depths (soundings) can be measured. For many marine and coastal applications, the vertical datum is the height of a specified sea or water surface, mathematically defined by averaging the observed values of a particular stage or phase of the tide, and is known as a tidal datum (Hicks, 1985).[1] It is important to note that as local phenomena, the heights of tidal datums can vary significantly from one area to another in response to local topographic and hydrographic characteristics such as the geometry of the landmass, the depth of nearshore waters, and the distance of a location from the open ocean (Cole, 1997).[2]

As almost every coastal resident knows, tides are a daily occurrence along the Massachusetts coast. Produced largely in response to the gravitational attraction between the earth, moon and sun, the tides of Massachusetts are semi-diurnal - *i.e.*, two high tides and two low tides each tidal day.[3] Although comparable in height, generally one daily tide is slightly higher than the other and, correspondingly, one low tide is lower than the other. Tidal heights vary throughout the month with the phases of the moon with the highest and lowest tides (referred to as spring tides) occurring at the new and full moons. Neap tides occur approximately halfway between the times of the new and full moons exhibiting tidal ranges 10 to 30 percent less than the mean tidal range (NOAA, 2000a).

Tidal heights also vary over longer periods of time due to the non-coincident orbital paths of the earth and moon about the sun. This variation in the path of the moon about the sun introduces significant variation into the amplitude of the annual mean tide range and has a period of

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[1] The definition of a tidal datum, a method definition, generally specifies the mean of a particular tidal phase(s) calculated from a series of tide readings observed over a specified length of time (Hicks, 1985). Tidal phase or stage refers to those recurring aspects of the tide (a periodic phenomenon) such as high and low water.

[2] For example, the relative elevation of MHW in Massachusetts Bay is on the order of 2.8 feet higher than that encountered on Nantucket Sound and 3.75 feet higher than that of Buzzards Bay.

[3] A tidal day is the time or rotation of the earth with respect to the moon, and is approximately equal to 24.84 hours (NOAA, 2000a). Consequently, the times of high and low tides increase by approximately 50 minutes from calendar day to calendar day.

approximately 18.6 years (a Metonic cycle), which forms the basis for the definition of a tidal epoch (NOAA, 2000a). In addition to the long-term astronomical effects related to the Metonic cycle, the heights of tides also vary in response to relatively short-term seasonal and meteorological effects. To account for both meteorological and astronomical effects and to provide closure on a calendar year, tidal datums are typically computed by taking the average of the height of a specific tidal phase over an even 19-year period referred to as a National Tidal Datum Epoch (NTDE) (Marmer, 1951). The present NTDE, published in April 2003, is for the period 1983-2001 superseding previous NTDEs for the years 1960-1978, 1941-1959, 1924-1942 and 1960-1978 (NOAA, 2000a) (Table 4).

Table 4. Common Tidal Datums (*Source: NOAA, 2000b).

Tidal Datum	Definition
Mean Higher High Water (MHHW)	Average of the highest high water (or single high water) of each tidal day observed at a specific location over the NTDE*
Mean High Water (MHW)	Average of all high water heights observed at a specific location over the NTDE*
Mean Sea Level (MSL)	Arithmetic mean of hourly tidal heights for a specific location observed over the NTDE*
Mean Tide Level (MTL)	Arithmetic mean of mean high and mean low water calculated for a specific location
Mean Low Water (MLW)	Average of all low water heights observed at a specific location over the NTDE*
Mean Lower Low Water (MLLW)	Average of the lowest low water (or single low water) of each tidal day observed at a specific location of the NTDE*

Field Work

Once a preliminary inventory of potential STPs was compiled in the desktop analysis, an extensive fieldwork assessment program was conducted to verify the presence or absence of the STP. When the presence of an STP was confirmed, the accurate horizontal and vertical location was obtained. A Trimble® R10 GNSS receiver utilizing Real-Time-Kinematic GPS (RTK-GPS) was used for all positioning and tide correction fieldwork. The Center subscribes to a proprietary Virtual Reference Station (VRS) network (KeyNetGPS) that provides virtual base stations via cellphone from Southern Maine to Virginia. This allows the Center to collect RTK-GPS without the need for a terrestrial base station or to post-process the GPS data, streamlining the field effort and increasing field work efficiency.

The Center performed a rigorous analysis of this system to quantify the accuracy of this network (Borrelli, et al., 2020). Over 25 National Geodetic Survey (NGS) and Massachusetts Department of Transportation (DOT) survey control points, with published state plane coordinate values relating to the Massachusetts Coordinate System, Mainland Zone (horizontal: NAD83; vertical NAVD88), were occupied. Control points were distributed over a wide geographic area of the Cape and Islands.

Multiple observation sessions, or occupations, were conducted at each control point with occupations of 1 second, 90 seconds, and 15 minutes. To minimize potential initialization error, the unit was shut down at the end of each session and re-initialized prior to the beginning of the next session. The results of each session (i.e., 1 second, 90 second, and 15-minute occupations) were averaged to obtain final x, y, and z values to further evaluate the accuracy of short-term occupation. Survey results from each station for each respective time period were then compared with published NGS and DOT values and the differences used to assess and quantify uncertainty. Significantly, there was little difference between the values obtained for the 1 second, 90 second, and 15-minute occupations. The overall uncertainty analysis for these data yielded an average error of 0.008 m in the horizontal (H) and 0.006 m in the vertical (V). An RMSE of 0.0280 m (H) and 0.0247 m (V) and a National Standard for Spatial Data Accuracy (95%) of 0.0484 m (H) and 0.0483 m (V).

The ability to conduct accurate fieldwork is a critical component of the STP verification process for several reasons. First, post processing of lidar collected via aerial surveys can introduce uncertainties that exaggerate or diminish features in three-dimensional data and, as a result, can obscure or conflate the presence and scale of an inundation pathway. These effects have been shown to be associated with 'bare earth' models where elevations tend to be "pulled up" adjacent to areas where buildings have been removed and "pulled down" in areas where bridges and roads cross streams or valleys (Figure 4).

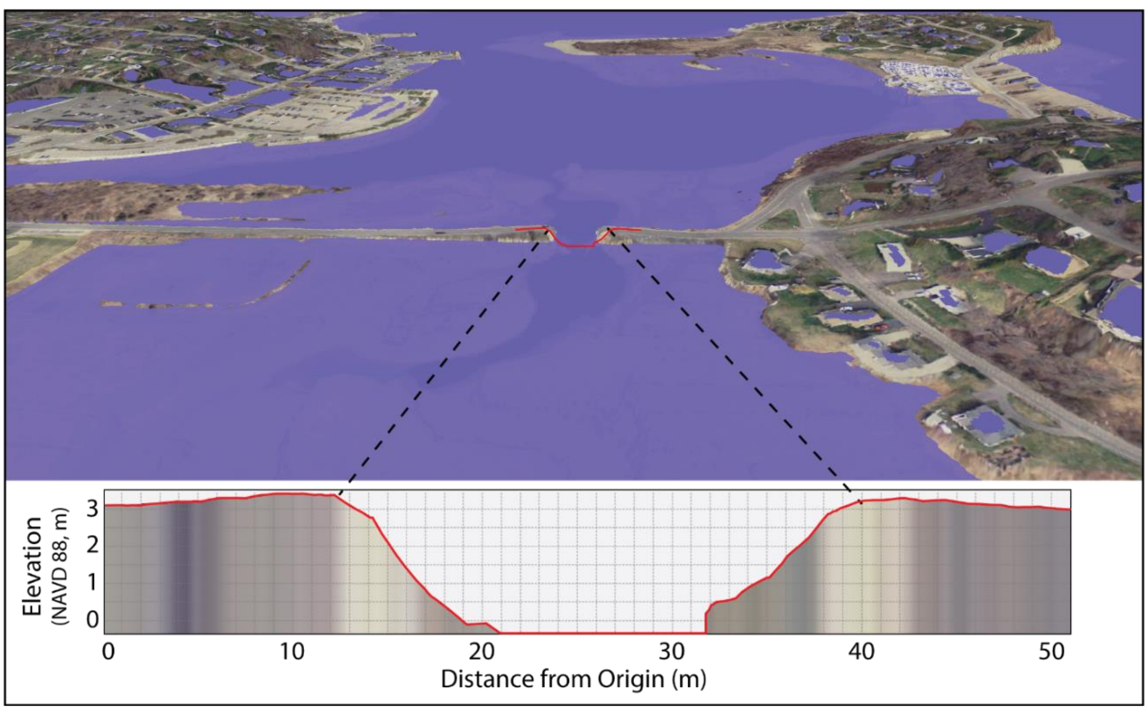

Figure 4. Example of 'pull down' at a bridge. The algorithm used to create the Lidar surface is designed to mimic natural topography. It seems to have given precedent to the natural tidal channel and classified the bridge as noise removing it from the surface. Profile units = meters (Vert. NAVD88, Hor. NAD83).

Second, the use of an RTK-GPS instrument provides the accuracy necessary for acquiring and verifying 3-dimensional positional data. In this way GPS data is used to corroborate or eliminate the presence of STPs identified in the desktop lidar analysis. Third, due to the dynamic nature of coastal environments, visual assessment conducted as part of the field work sometimes reveals STPs that are not revealed in a desktop analysis of lidar data. Lastly, and also related to the ephemeral characteristics of the areas proximate to the shoreline, even the most current lidar is frequently out of date in dynamic areas. Consequently, the GPS survey, coupled with field observation of each STP, provides real time information to eliminate STPs that may have appeared in the lidar but no longer exist due to changes in landform .

At the completion of the desktop analysis, all potential STPs were compiled into a spatial database with x, y, z coordinates and uploaded into the Center's GPS. Using the "stakeout" function and aerial photographs to navigate to the precise location identified with the lidar, each potential STP location, and the adjacent area, is inspected by a 2-3-person team and occupied with the GPS mobile unit. This served four purposes, first to map the real-world location of the STP identified during the desktop analysis; second to increase the positional accuracy of the verified STP itself; third, to verify consistency with the current landscape setting; and lastly to confirm the positional accuracy of the lidar data.

Significantly, using the GPS instrument to navigate to the location of a potential STP also afforded the field crew the opportunity to investigate potential alternative or additional STPs based on visual inspection of the area. Many coastal sites have very low relief (relatively flat) and verifying whether an STP existed, its exact location, and the direction of water flow required professional judgment and experience in the principles and practices of land surveying as well as a thorough knowledge of coastal processes.

After the field work was completed, the team returned to the laboratory to remove those points determined not be STPs from the database, incorporate newly identified STPs documented in the field, and provide all STPs with horizontal and vertical position information, substrate and geographic context labels, photograph links, and other pertinent information for inclusion into a comprehensive database. Once the information was quality controlled, the database was brought into the project GIS for use as an interactive archive of final STP information. Importantly, the database was annotated to note those areas where the lidar was found to correlate poorly with current conditions or real-world position as determined by the GPS observations and professional judgment which was necessary to accurately represent the STP.

With the final compilation of the STP spatial database, the file was brought into ESRI's ArcGIS to provide a working or living archive for local managers: 1) to proactively identify and prioritize which STPs to address prior to storm events; 2) to prepare for approaching storms; and 3) to plan for longer-term improvements to mitigate other STPs.

To increase the utility of the STP data and make visualizations more user friendly for local managers, inundation planes were created. After several attempts at visualizing STPs and recognizing that floodplain mapping was not a goal of the project, it was felt that the use of planes would be the clearest way of making the data useful while addressing the uncertainty associated with the lidar. After reviewing the various scenarios, the lower end of the planes was begun at the highest Spring tide of the year. Planes were developed in 6-inch intervals to a maximum elevation of the Storm of Record plus four feet and planes extracted for each range. In addition to providing an upper limit to project elevations, it was felt that using the Storm of Record plus 4 feet provides a useful representation of future sea level rise scenarios that would have practical implications for local managers.

No data are collected on private property. If a point was inaccessible to the field team, it was labeled as an *unverified* STP, meaning the STP was identified as a potential STP in the desktop analysis, but due to circumstances it was inadvisable (e.g. private property) or impossible (e.g. beneath substantial tree cover) for the field team to 'occupy' the potential STP. Unverified STPs are not indicative of a lack of hazard, rather because it was chosen as a potential STP it warrants further investigation by the towns. The field team adjusts the STP location based on the real-world conditions if needed by selecting the lowest elevation point if the STP identified in the desktop analysis does not reflect the on-the-ground topography.

RESULTS AND DISCUSSION

The desktop analysis of the lidar data yielded 443 potential STPs throughout Cohasset and Scituate (Table 5, Figure 5). Field work for this study was conducted over 5 days (19 November, 13 December 2019; 13 January, 18 and 21 March 2020). Typically, the field team drove to the field site together and conducted work in a truck owned by the Center for Coastal Studies. However, the last two days of field data collection (18, 21 March 2020), field team members drove to each potential pathway location in separate cars, did not share equipment, and observed 6 feet of social distancing throughout the day due to the onset of the Covid-19 pandemic in the region.

Each potential STP identified in the desktop analysis was inspected by the field team and the location was moved when observations by the field team determined that the lidar no longer reflected the present-day terrain in 2019-2020. During the field work 202 pathways (43% of the total) were moved more than 1 m horizontally to better reflect current, real-world conditions.

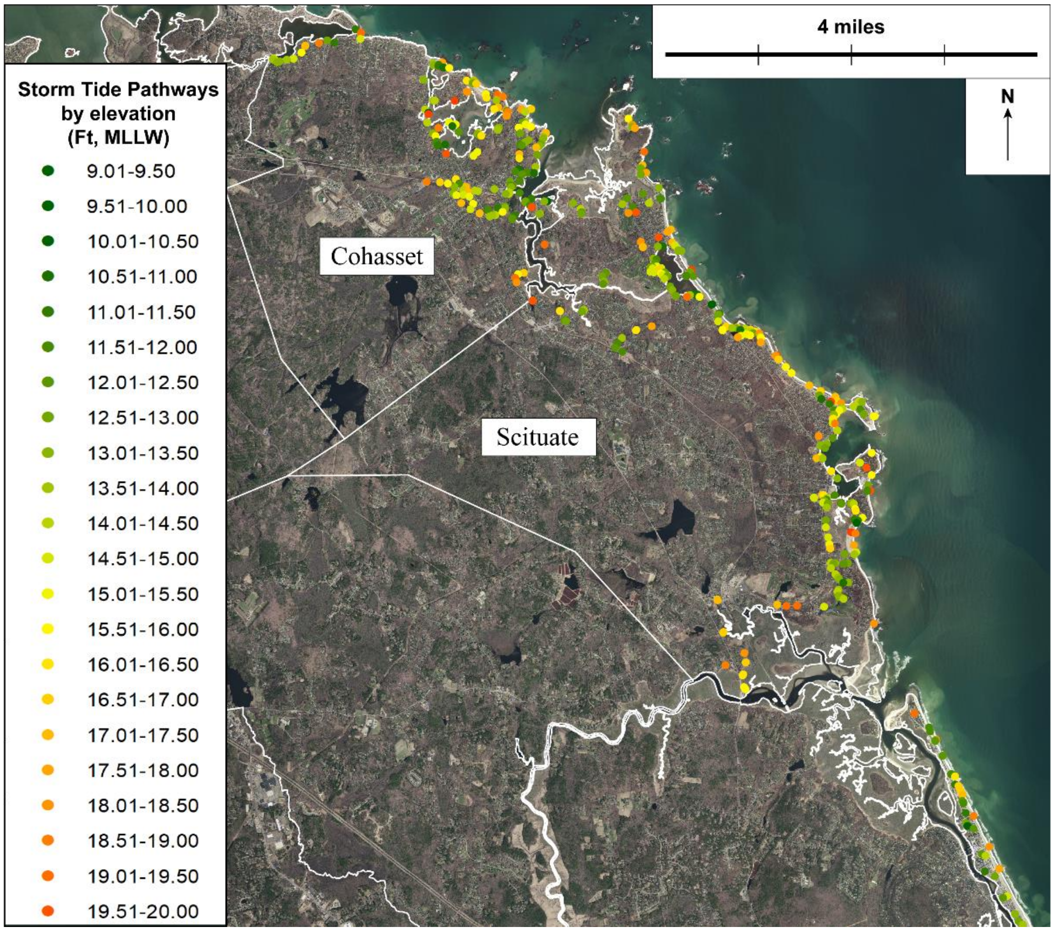

Figure 5. Location of the storm tide pathways for the study area. STPs are color-coded by elevation.

In addition, the field team located low-lying areas that were not captured in the lidar data during desktop analysis or added more STPs in the field to better reflect the present day topography and/or vulnerability, highlighting the need for field-based verification of each potential STP. A total of 28 additional STPs were added during the course of this study yielding a total of 465 storm tide pathways for the study area. The Town of Cohasset had 166 pathways and the Town of Scituate had 299 pathways. Several types of STPs are included in this dataset: standard storm tide pathways (STPs) as discussed above; 'spillways' (STP-S); 'roadways' (STP-R); and unverified (STP-U) (Table 6). These sub-types were developed to reflect different on-the-ground morphologies and techniques needed to identify and/or describe potential inundation at these locations.

Table 5. Storm tide pathways in Scituate and Cohasset by elevation.

Elevation Range (MLLW, ft.)	Number of STPs
9.01-9.50	5
9.51-10.00	1
10.01-10.50	7
10.51-11.00	13
11.01-11.50	20
11.51-12.00	33
12.01-12.50	31
12.51-13.00	49
13.01-13.50	54
13.51-14.00	30
14.01-14.50	32
14.51-15.00	27
15.01-15.50	19
15.51-16.00	29
16.01-16.50	17
16.51-17.00	20
17.01-17.50	23
17.51-18.00	12
18.01-18.50	16
18.51-19.00	10
19.01-19.50	9
19.51-20.00	8

The ‘standard’ STP can be described as a relatively narrow low-lying area where flowing water would be directed inland via a natural or human made depression in topography (Figure 6). A low-lying channel or other depression, or conversely a series of elevated topographic features, could channelize flow into an area. Stopping flow at that STP could prevent inundation for a given elevation. Each STP has a Pathway Activation Level (PAL) at which water will begin to flow. For example, the PAL for the STP in Figure 6 is 14.30 ft (MLLW). Therefore, when the water level reaches 14.30 ft (MLLW) regardless of the driver (i.e. storm surge, waves, sea level rise) water will begin to flow at this point. Using the PALs town staff can prioritize the most vulnerable STPs as efficiently and effectively as possible.

Table 6. Storm Tide Pathways for Scituate and Cohasset.

Storm Tide Pathways	Standard (STP)	Spillway (STP-S)	Roadway (STP-R)	Unverified (STP-U)
465	179	90	61	135

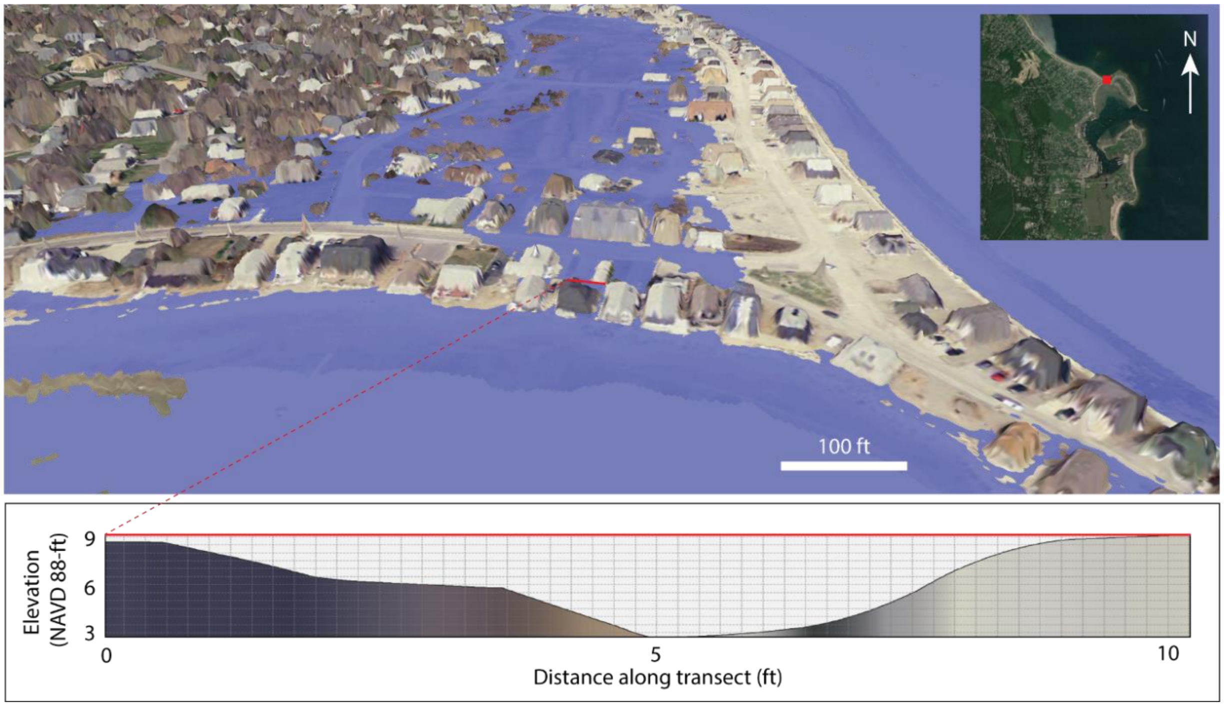

Figure 6. Example of a STP in Scituate. The elevation of the water level in the image is (15.00 ft MLLW). The STP is activated at 14.30 ft MLLW).

The term 'spillway' was developed to reflect the low relief of the area. The STP-S are situated in very flat areas and are representative of long broad weir-like formations as opposed to the discrete point-like nature of the standard STPs (Figure 7). Actions planned to mitigate spillway STPs generally require action along a broad area and detailed topographic surveys in order to minimize associated flooding during future events. While difficult to visualize, these areas may be of great concern precisely because of the characteristic that makes them a spillway, a broad flat area of inundation with no clear, narrow pathway for flood waters to enter.

Figure 7. Example of topography consistent with a spillway STP. Almost 20% of the STPs mapped in the study were spillways. These areas will require a more extensive and concerted efforts to address.

Finally, an unverified STP (STP-U) was defined to be an STP that was identified during the lidar analysis, but was unable to be located or occupied by the field team. The lidar used for this study is a ‘bare earth’ lidar data set, which is typical for these types of analyses. As discussed above, during the processing of these data the vegetation, (trees, bushes, beach grass, salt marsh, etc.) and structures (houses, buildings, etc.) are removed from the data, hence the ‘bare earth’ name. Therefore, certain low spots found in the lidar analysis could not be accessed or were otherwise inaccessible (private property) or may, in fact, have been artifacts of the bare-earth process. The 135 STP-Us found in this study are in low areas that will experience water flowage but the precise location of the STP is not identifiable using solely the desktop analysis. This is either due to conditions changing naturally (e.g. coastal dunes) or human-induced (construction, development) since lidar was collected or the STP being located on private property. For the former, new surveys can be conducted by field teams using drones or when new lidar becomes available. For the latter, further field work will require permission to enter private property. All of these STP-U’s are included in the final data as many of them are likely STPs and should be of interest to the towns.

Future Considerations

Prior to the Blizzard of 2018 only town staff that had witnessed the Blizzard of ‘78 could speak to the water elevations seen during a storm of record. However, many STPs are just above water elevation seen in the 2018 storm, the new storm of record. In fact, mapping revealed that 54 STPs are less than 12 inches above the storm of record (14.78 ft MLLW) (Figure 8). In other words, 54 locations throughout Scituate and Cohasset that have never been flooded before would be inundated with another 12 inches of water level beyond that last storm of record. This water elevation could be achieved singularly or with a combination of a higher tides, storm surge, waves, or sea level rise. A total of 25 of those 54 STPs would flood with only 6 inches of increased water level.

According to NOAA’s Boston tide gauge data (tidesandcurrents.noaa.gov/stationhome.html?id=8443970), the storm surge that occurred during the Blizzard of 2018 was 3.11 ft, that coupled with the spring tide on January 4th produced a total water level of 14.78 ft (MLLW) in Scituate. During a storm that peaked on January 27th, 2015 the storm surge measured at the Boston tide gauge was 4.71 ft, a 1.60 ft difference, demonstrating that storms with surges of this magnitude are not outside the realm of possibility. Had the 2018 storm occurred with a storm surge similar to that of the 2015 storm, the total water level could have approached 16.4 ft (MLLW), this could have flooded more than the 54 STPs noted above and inundated hundreds of more acres throughout the study area.

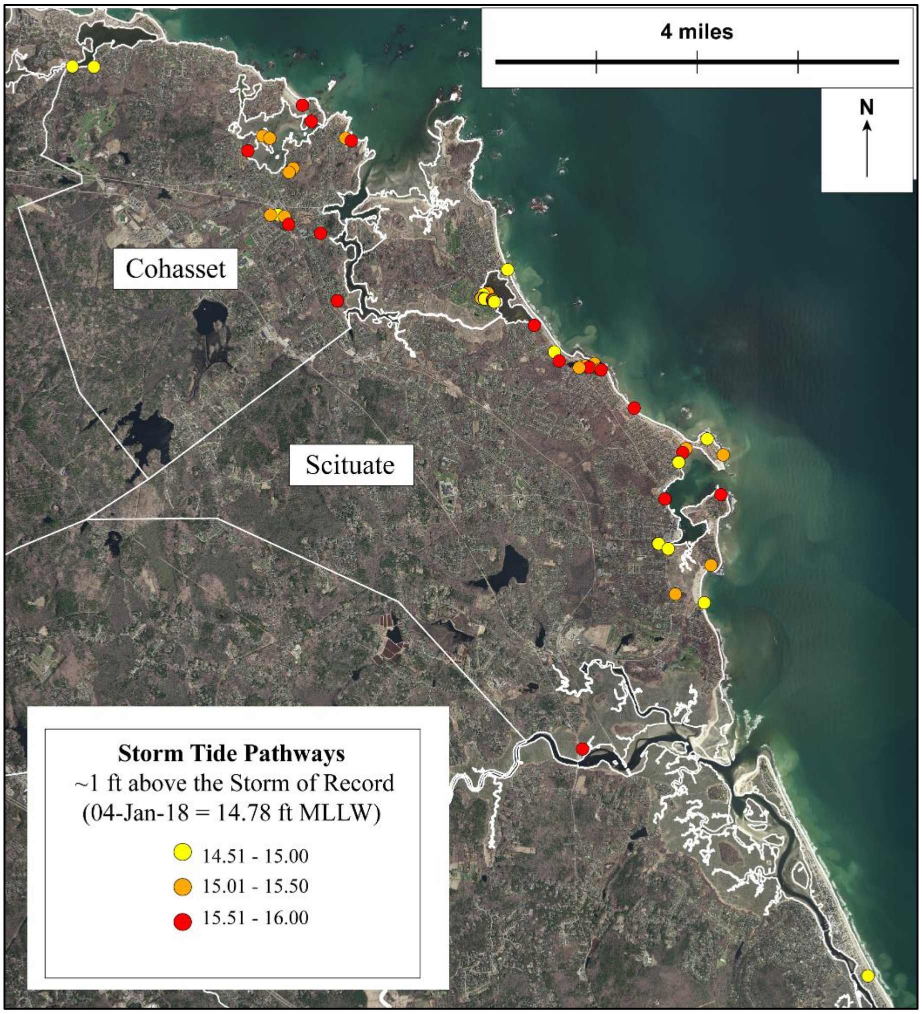

Figure 8. Storm Tide pathways throughout the study area that are <12 inches above the storm of record. These areas have not flooded due to storm tides (storm surge, high tides, waves, etc.) during recorded history.

Low-lying coastal areas are susceptible to inundation from nuisance, or sunny day flooding, storm surge and sea level rise. The low-lying portions of the Towns of Scituate and Cohasset are particularly vulnerable. Using data generated for this study it has been shown that on average approximately 100 acres of land will be inundated for every 6 inches of rise in total water level from 10.5 – 20.0 ft (MLLW) in any form (Figure 9). The mean spring tide elevation was 9.93 ft (MLLW) for the study area. Starting at 10.0 – 10.50 ft (MLLW), for each 6-inch increase in water level there is, on average, a commensurate inundation of ~100 acres throughout the study area, this ranges from a low of 68.41 acres between 18.5 – 19.0 ft, to a high of 143.56 acres between 10.0 - 10.5 ft. These types of STP data can be helpful in numerous ways. Towns can design long-term planning efforts to address inundation resulting from sea level rise and increasing frequency of nuisance, or sunny day flooding. Additionally, short-term, storm preparation and proactive mitigation can be developed. The mapping of STP data has helped Provincetown and Truro prepare for approaching storms. Town staff monitor real-time total water level predictions from the NWS and ready the needed mitigation efforts for low-lying STPs throughout town, such as sandbags, portable flood walls, and cordoning off potential hazardous roads for vehicles or pedestrians.

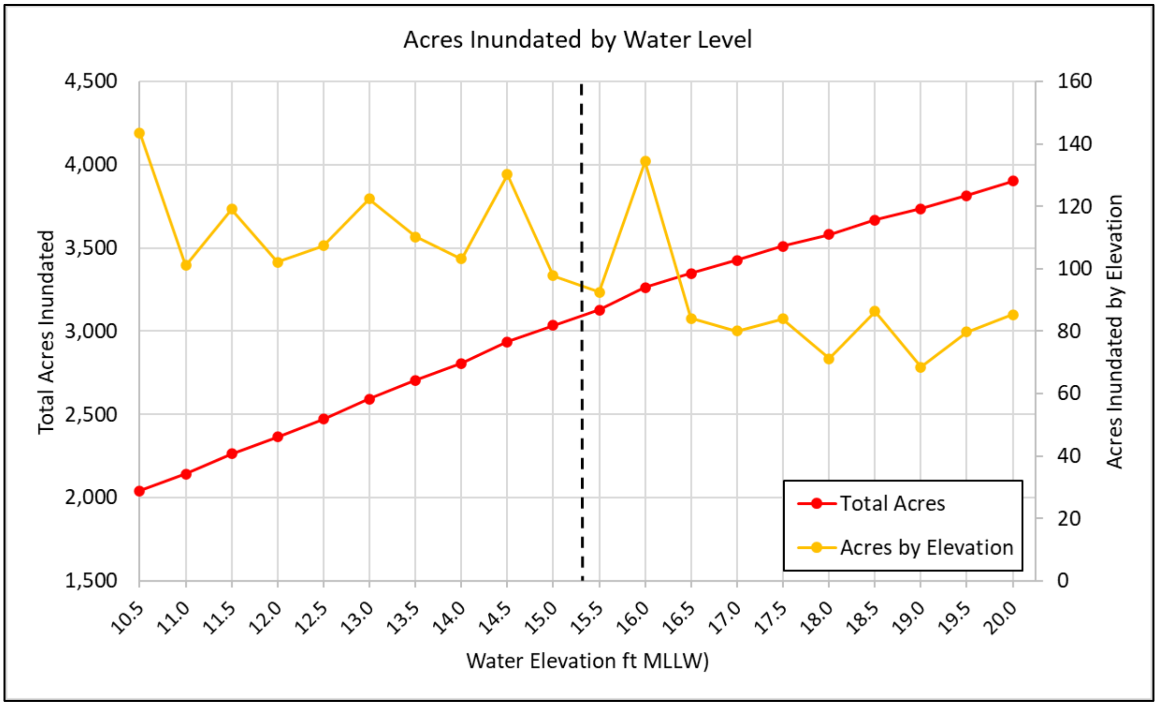

Figure 9. Acres of Inundation. Red line is total cumulative acres inundated with each 6-inch increase in water level. Yellow line is the acres inundated for each individual 6-inch increase in water level. The average is approximately 100 acres per 6-inch increase in sea level rise.

Coastal Flood Threat and Inundation Mapping webpage

SNEWFO-NWS maintains a webpage (https://www.weather.gov/box/coastal) with tide and storm surge forecasts for numerous stations throughout southern New England. As coastal storms approach, viewers can manipulate the webpage to depict the approximate extent and depth of flooding based on the predicted tide stage and forecasted storm surge. As noted on the webpage these layers are based on 'static water surface elevations' and are shown in 0.5 ft increments. Wave modeling is not incorporated into these storm-related forecasts. Using a DEM with 5-meter grid cell, location-specific water level data, and the results of storm surge forecasting, the webpage provides users with a 'total water level' forecast and projects potential inundation threats as a coastal storm approaches a given coastal area (e.g. Scituate Harbor). The data from this project will be given to the SNEWFO-NWS and will be displayed on their website after internal review is completed. Additionally, these data will also be hosted on the CCS webpage (https://coastal studies.org/) in late summer of 2020.

The ranges provided to the SNEWFO-NWS begin at the highest high tide of the year and increase to an elevation equal to the 2018 storm of record plus 4 feet in 0.5 foot increments (10.0 – 20.0 ft

MLLW) for 20 inundation layers. The additional 4 ft of STPs were included to account for the potential effects of sea level rise on nuisance and storm flood conditions. These data were then grouped into four flooding categories used by NWS in its forecast: *Action (11.0 ft MLLW)*, *Minor* (11.5 ft MLLW), *Moderate* (13.5 ft MLLW) and *Major* (15.5 ft MLLW) (Table 7).

Table 7. Storm Tide Pathways within National Weather Service flood stages.

NWS Flood Stages	Elevation (MLLW)	Storm Tide Pathways
Action	11.0	20
Minor	11.5	167
Moderate	13.5	107
Major	15.5	145

Combining the results from the 2 towns a total of 465 pathways (166 in Cohasset, 299 in Scituate) were identified for areas located along the Scituate/Cohasset shoreline and these point data will be provided as 'shapefiles' to the NSW. The horizontal planes (10.0 MLLW to 20.0 MLLW) at 0.5 ft intervals that were generated for this project throughout the study area will also be provided to the NWS. Working with staff at SNEWFO-NWS, these shapefiles are imported into the Coastal Flood Threat and Inundation Mapping website and color coded to correspond to NWS Minor and Moderate and Major flooding categories. The updated webpage using these project data, when internal NWS review is completed, can be viewed at https://www.weather.gov/box/coastal.

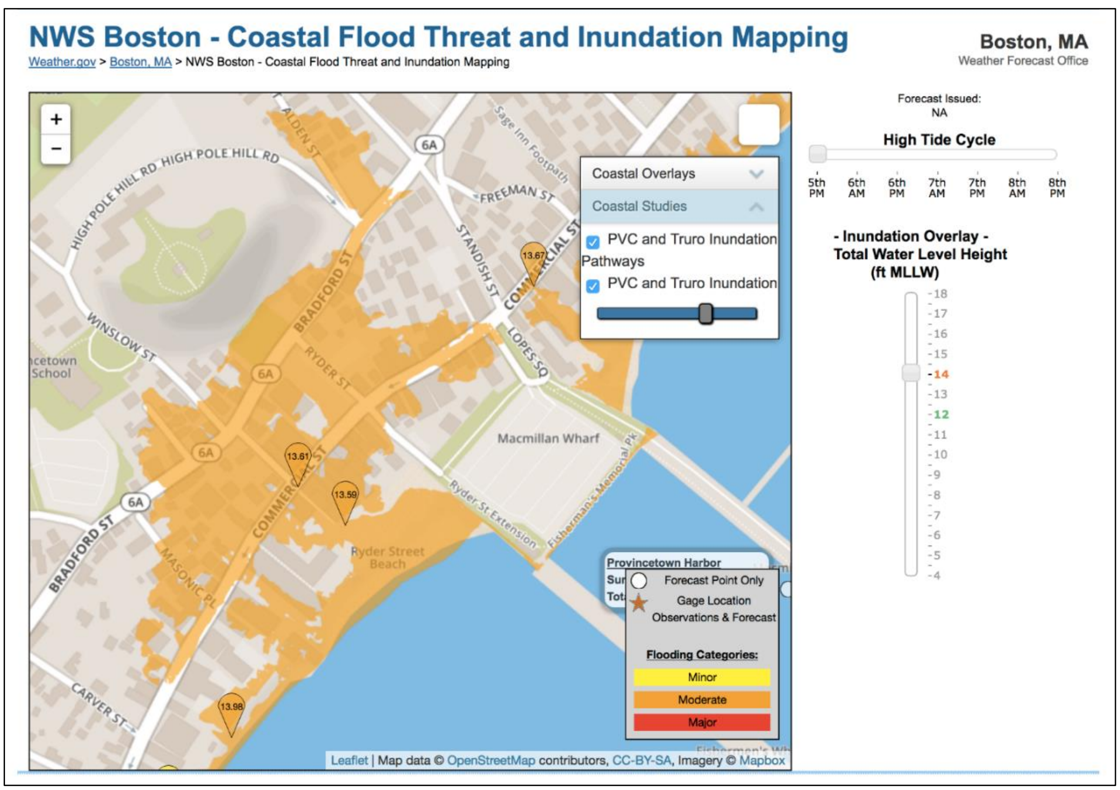

Figure 10. Example of NWS website showing STPs and extents of inundation in downtown Provincetown. A similar map package will be available for the towns of Scituate and Cohasset pending internal review by the NWS.

Appendix A

A Summary of References Concerning Major Coastal Storm Events, Associated Storm Tide Elevations, and Tidal Datums

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